DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
CECW-EE **Washington, DC 20314-1000**

Technical Letter
No. 1110-2-549

30 November 1997

Engineering and Design
RELIABILITY ANALYSIS OF NAVIGATIONAL LOCK AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT

1. Purpose

This engineer technical letter (ETL) provides guidance for assessing the reliability of mechanical and electrical systems of navigational locks and dams and for establishing an engineering basis for major rehabilitation investment decisions.

2. Applicability

This ETL applies to all USACE Commands having responsibilities for civil works navigational lock and dam projects.

3. References

ER 1130-2-500
Project Operations-Partners and Support (Work Management Policies)

EP 1130-2-500
Project Operations-Partners and Support (Work Management Guidance and Procedures)

EC 11-2-172
Annual Program and Budget Request for Civil Works Authorities, Corps of Engineers, FY99

ETL 1110-2-532
Reliability Assessment of Navigation Structures

ETL 1110-2-550
Reliability Analysis of Hydropower Equipment

MIL-STD-756B
Military Standard: Reliability Modeling and Prediction

American National Standards Institute/ANSI/ IEEE Std 493-1980
Design of Reliable Industrial and Commercial Power Systems

Bloch and Geitner 1994
Bloch, H. P., and Geitner, F. K. 1994. "Practical Machinery Management for Process Plants, Volume 2; Machinery Failure Analysis and Troubleshooting," Gulf Publishing Company, Houston, TX.

Green and Bourne 1972
Green, A. E., and Bourne, A. J. 1972. *Reliability Technology*, Wiley Interscience, London, New York.

Krishnamoorthi 1992
Krishnamoorthi, K. S. 1992. *Reliability Methods for Engineers*, ASQC Quality Press, Milwaukee, WI.

Mlakar 1994
Mlakar, P. F. 1994. "Reliability of Hydropower Equipment," Jaycor Report No. J650-94-001/1827, Vicksburg, MS.

Modarres 1993
Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis*, Marcel Dekker, Inc., New York.

Naval Surface Warfare Center 1992
Naval Surface Warfare Center. 1992. "Handbook of Reliability Prediction Procedures for Mechanical Equipment," NSWC-92/L01, Carderock Division, Dahlgren, VA.

Reliability Analysis Center 1994
Reliability Analysis Center. 1994. "NPRD Nonelectronic Parts Reliability Data, 1995," Rome, NY.

Sadlon 1993
Sadlon, R. 1993. "Mechanical Applications in Reliability Engineering," Reliability Analysis Center, Rome, NY.

4. Distribution Statement

Approved for public release, distribution is unlimited.

5. Background

a. Navigational lock and dam facilities are an important link in the nation's transportation system. Their mission is to maintain the navigable waterways and allow both cargo transport and recreational traffic between adjacent segments of the waterways. Mechanical and electrical components at these facilities function as systems to operate the various gates and valves. Breakdowns and poor performance of these systems can cause delays to navigation and adversely affect the overall national economy.

b. Lock and dam major rehabilitation projects began being budgeted under the Construction, General, and Flood Control, Mississippi River and Tributaries appropriation account in FY 93. To qualify as major rehabilitation projects, work activities must extend over two full construction seasons and the total required implementation costs must be greater than a certain minimum threshold. The threshold amounts are adjusted annually for inflation as published in the Annual Program and Budget Request, EC 11-2-172. To successfully compete as new starts, major rehabilitation proposals must be supported by the same level of economic analysis as new water resource projects. Chapter 3 of ER 1130-2-500 establishes policy for major rehabilitation at completed Corps projects. Chapter 3 of EP 1130-2-500 establishes guidance for the preparation and submission of major rehabilitation project evaluation reports for annual program and budget submissions.

c. The rehabilitation of mechanical and electrical equipment is usually included as part of the overall project. Mechanical and electrical component rehabilitation may include replacement and/or reconditioning to restore or improve a system to a like-new condition. The rehabilitation may be considered from various perspectives. It may be necessary to restore existing equipment that has deteriorated with time or failed in service, or equipment may become obsolete and replacement might be desired to upgrade the equipment to modern standards. The major rehabilitation evaluation reports and supporting information will have to provide evidence of criticality with a certain level of detail based on specific uniform engineering criteria. Reliability assessments based on probabilistic methods provide more consistent results and reflect both the condition of existing equipment and the basis for design.

d. Further guidance for the reliability evaluation of hydropower equipment has been published in ETL 1110-2-550 and Mlakar (1994). Guidance for the reliability assessment of navigation structures is included in ETL 1110-2-532.

6. Reliability Concepts and Definition of Terms

a. *Definition of terms.*

(1) Component. A piece of equipment or portion of a system which is viewed as an independent entity for purposes of evaluation; i.e., its reliability does not influence the reliability of another component.

(2) System. An orderly arrangement of components that interact among themselves and with external components, other systems, and human operators to perform some intended function.

(3) Failure. Any trouble with a component that causes unsatisfactory performance of the system.

(4) Hazard function or failure rate. The instantaneous probability of failure of an item in the next unit of time given that it has survived up to that time. It is the mean number of failures of a component per unit exposure time.

(5) Reliability. The probability that an item will perform its intended function under stated conditions, for either a specified interval or over its useful life.

(6) Basic reliability. Basic reliability measures the demand for maintenance and logistic support of a system caused by an item's unreliability.

(7) Mission reliability. Reliability as a measure of operational effectiveness of a system. A mission reliability prediction estimates the probability that items will perform their required functions during a mission.

(8) Unsatisfactory performance. Sub-standard operation; partial or complete shutdown of the system; operation of safety devices; unexpected deenergization of any process or equipment.

b. *Measures of component reliability*

(1) Reliability function. The continuous probabilistic approach to item reliability is represented by the reliability function. It is simply the probability that an item has survived to time t. The mathematical expression can be summarized by:

$$R(t) = P(T \geq t) \qquad (1)$$

where

t = the designated period of time for the item's operation

T = time to item failure

$P(T \geq t)$ = probability that the time to failure of an item will be greater than or equal to its service time

$R(t)$ = reliability of the item, i.e. probability of success

Conversely, the probability of failure $F(t)$ is simply:

$$F(t) = 1 - R(t) \qquad (2)$$

(2) Hazard function or failure rate. The hazard function $h(t)$ represents the proneness to failure of a component as a function of its age or time in operation. It reflects how the reliability of a component changes with time as a result of various factors such as the environment, maintenance, loading, and operating condition. From the reference literature, it can be shown that:

$$h(t) = \frac{f(t)}{R(t)} \qquad (3)$$

where

$f(t)$ = Probability density function (pdf). It is the limiting curve of the relative frequency of occurrences of a particular random variable as the sample approaches infinity.

The hazard function or instantaneous failure rate is the conditional probability of failure of an item in the next unit of time given that it has survived up to that time. The hazard function can increase, decrease, or remain constant. It has been shown that the failure rate behavior of most mechanical and electrical engineering devices follows that shown in Figure 1. This is known as the *bathtub curve*. Region A represents a high initial failure rate which decreases with time to nearly constant. This is known as the infant mortality region and is a result of poor workmanship or quality control. Region B represents the useful life phase. Here, failures occur because of random events. Region C represents the wearout phase where failures occur due to complex aging or deterioration.

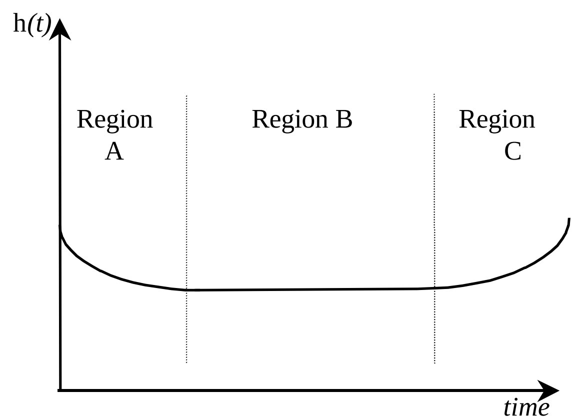

Figure 1. Typical Bathtub Curve

The flat random or chance failure region (Region B) of the curve for electromechanical devices is much longer than the other two regions. Electrical devices exhibit a much longer chance failure period relative to mechanical devices. Methods presented in this document will attempt to determine reliability and predict the characteristics of Regions B and C of the bathtub curve for mature equipment using the common continuous distribution functions discussed in the next sections. The infant mortality region (Region A) will not be directly discussed in this ETL since the equipment considered for major rehabilitation projects usually falls in Regions B or C.

(3) Exponential distribution. Exponential distribution is the most commonly used distribution in reliability analysis. The reliability function is:

$$R(t) = e^{-\lambda t} \qquad (4)$$

where

t = time

λ = failure rate

This distribution can be used to represent the constant hazard rate region (Region B) of the bathtub curve. The hazard function for the exponential distribution remains constant over time and is represented as simply λ:

$$h(t) = \lambda \qquad (5)$$

Plots of the reliability and hazard functions for the exponential distribution are shown in Figures 2 and 3.

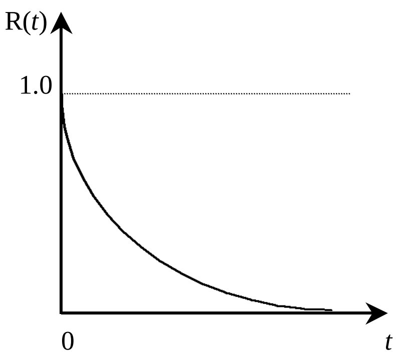

Figure 2. Reliability Function for Exponential Distribution

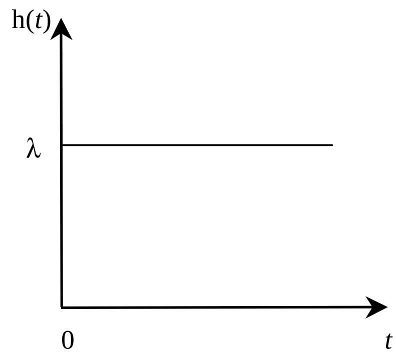

Figure 3. Hazard Function for Exponential Distribution

The average or mean of the exponential life distribution is the mean time to failure (MTTF). It is the average length of life of all units in the population. It has significance in that the reciprocal of the hazard rate is equal to the MTTF:

$$\text{MTTF} = \frac{1}{\lambda} \qquad (6)$$

(4) Weibull distribution. The Weibull distribution is a generalization of the exponential distribution. This distribution covers a variety of shapes and its flexibility is useful for representing all three regions of the bathtub curve. The Weibull distribution is appropriate for a system or complex component made up of several parts. The Weibull reliability function is:

$$R(t) = \exp\left[-\left(\frac{t}{a}\right)^{b}\right] \qquad (7)$$

where

α = the scale parameter or characteristic life

β = the shape parameter

For 0 < β < 1, the Weibull distribution characterizes wear-in or early failures. For β = 1, the Weibull distribution reduces to the exponential distribution. For 1 < β < ∞, the Weibull distribution characterizes the wear-out characteristics of a component (increasing hazard rate). The Weibull hazard function is:

$$h(t) = \frac{b}{a}\left(\frac{t}{a}\right)^{b-1} \qquad (8)$$

Plots of the reliability and hazard functions for the Weibull distribution are shown in Figures 4 and 5.

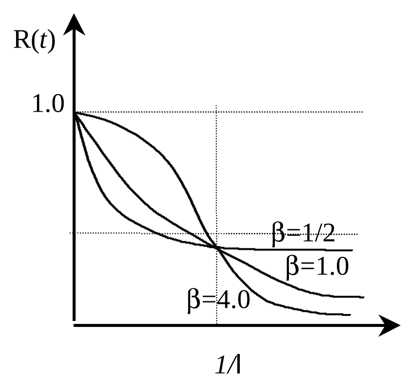

Figure 4. Reliability Function for Weibull Distribution

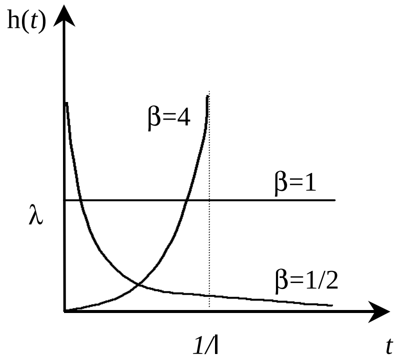

Figure 5. Hazard Function for Weibull Distribution

c. *General data required*. Reliability analyses provide the best estimate of the reliability anticipated from a given design within the data limitations and to the extent of item definitions. The required data are dependent on the availability and depth of analysis required. Mechanical and electrical components are typically complex and made up of many different parts, each with several modes of failure. These failure modes are associated with many ambiguous variables such as operating environment, lubrication, corrosion, and wear. Historic data for lock and dam equipment is not usually available nor is it collected by controlled and tested means. These deficiencies require the analysis of equipment to be completed through the use of data from larger systematic samples of similar equipment such as the published failure rate data source of the Reliability Analysis Center (1994). Failure rate data can also be obtained by multivariate methods developed in the "Handbook of Reliability Prediction Procedures for Mechanical Equipment" (Naval Surface Warfare Center 1992). Prior to any reliability determination, investigations should be conducted to gain a thorough knowledge of the mechanical and electrical requirements and layouts, to identify equipment deficiencies, and to learn the project history and future demands.

7. Engineering Reliability Analysis

Assessing the reliability of a system from its basic elements is one of the most important aspects of reliability analysis. As defined, a system consists of a collection of items (components, units, etc.) whose proper, coordinated function leads to its proper operation. In a reliability analysis, it is therefore important to model the reliability of the individual items as well as the relationship between the various items to determine the reliability of the system as a whole. This ETL applies the reliability block diagram (RBD) method as outlined in MIL-STD-756B to model conventional probability relationships of collections of *independent* components and systems.

8. System Reduction

Determining the number of discrete mechanical and electrical components in a lock and dam requires system reduction to reduce the vast complexity of numerous components into smaller groups of critical components. Reliability models should be developed to the level of detail for which information is available and for which failure rate (or equivalent) data can be applied. Functional elements which are not included in the mission reliability model shall be documented and rationale for their exclusion shall be provided.

9. Component Reliability

The failure distribution appropriate to the specific electronic, electrical, electromechanical, and mechanical items should be used in computing the component reliability. In most cases, the failure distribution will not be known and the exponential or the Weibull function may be assumed. The α and β parameters of the Weibull equation are normally empirically determined from controlled test data or field failure data. This ETL presents a procedure for estimating these values. If the β value in the Weibull function is unknown, a value of 1.0 should be assumed. The flat failure region of mechanical and electrical components is often much longer than the other two regions, allowing this assumption to be adequate. Once the component reliability values are determined, the RBD method is used to evaluate their relationship within the system to determine the total system reliability. Appendices C and D contain more information on determining component reliability.

10. System Risk Analysis Using Block Diagrams

The necessity for determining the reliability of a system requires that the reliability be considered from two perspectives, basic reliability and mission reliability. Both are separate, but companion, products which are essential to adequately quantify the reliability of a system. The incorporation of redundancies and alternate modes of operation to improve mission reliability invariably decreases basic reliability. A decrease in basic reliability increases the demand for maintenance and support. Basic reliability is normally applied to evaluate competing design alternatives.

a. Basic reliability - series system model. A basic reliability prediction is a simplified model that is intended to measure overall system reliability. It is used to measure the maintenance and logistic support burden required by the system. A basic reliability model is an all-series model. Accordingly, all elements providing redundancy or parallel modes of operation are modeled in series. In a series system, the components are connected in such a manner that if any one of the components fail, the entire system fails. Care should be taken when developing this type of model since the final value of the basic reliability of the system is inversely proportional to the number of components included in the evaluation; i.e., the more components there are, the lower the reliability. Such a system can be schematically represented by an RBD as shown in Figure 6.

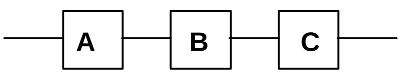

Figure 6. Series System

For a system with N mutually *independent* components, the system reliability for time t is:

$$R_S(t) = R_A(t)*R_B(t)*R_C(t)*\ldots*R_N(t) \qquad (9)$$

It can also be shown that if $h_s(t)$ represents the hazard rate of the system, then:

$$h_s(t) = \sum_{i=1}^{n} h_i(t)$$

(10)

The failure rate of a series system is equal to the sum of the failure rates of its components. This is true regardless of what the failure distributions of the components are.

b. Mission reliability. The mission reliability model utilizes the actual system configuration to measure the system capability to successfully accomplish mission objectives. The mission reliability model may be series, parallel, standby redundant, or complex. An example of lock and dam mission reliability is given in Appendix B.

(1) *Parallel system model.* In a parallel system, the system fails only when all of the components fail. Such a system is represented in Figure 7. In this configuration, the system will still perform if at least one of the components is working.

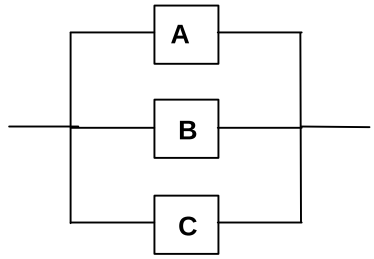

Figure 7. Parallel System

The reliability for the system is given by:

$$R_S(t) = 1-(1-R_A(t))(1-R_B(t))(1-R_C(t)) \qquad (11)$$

or

$$R_S(t) = 1-\prod_{i=1}^{N} (1 - R_i(t)) \qquad (12)$$

A more general form of a parallel system is the "*r* out of *n*" system. In this type of system, if any combination of *r* units out of *n independent* units arranged in parallel work, it guarantees the success of the system. If all units are *identical,* which is often the case, the reliability of the system is a binomial summation represented by:

$$R_S(t) = \sum_{j=r}^{n} \binom{n}{j} R(t)^j (1 - R(t))^{n-j} \qquad (13)$$

where

$$\binom{n}{j} = \frac{n!}{j!(n-j)!} \qquad (14)$$

The hazard rate for parallel systems can be determined by using:

$$h_s(t) = \frac{-d \ln R_s(t)}{dt} \qquad (15)$$

or

$$h_s(t) = \frac{-\mathrm{d} \ln[1-\prod_{i=1}^{N}(1-R_i(\mathrm{t}))]}{\mathrm{dt}} \qquad (16)$$

The result of $h_s(t)$ becomes rather complex and the reader is referred to the reference literature.

(2) *Standby redundant system.* A two-component standby redundant system is shown in Figure 8. This system contains equipment that is in primary use and also equipment standing idle ready to be used. Upon failure of the primary equipment, the equipment standing idle is immediately put into service and switchover is made by a manual or automatic switching device (SS).

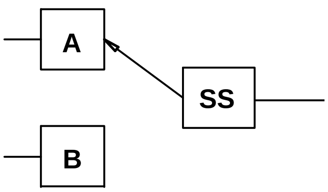

Figure 8. Standby Redundant System

The system reliability function for the exponential distribution can be calculated for a two-component, standby redundant system using the following equation:

$$R_S(t) = R_A(t) + \frac{(\lambda_A R_B(t))}{(\lambda_A + \lambda_{SS} + \lambda'_B - \lambda_B)} \left[1 - \exp(-(\lambda_A + \lambda_{SS} + \lambda'_B - \lambda_B) d_i t)\right] \quad (17)$$

where

d_i = duty factor for respective failure rate

λ'_B = hazard rate of the standby equipment while not in use

(3) *Complex system models.* Complex systems can be represented as a series-parallel combination or a non-series-parallel configuration. A series-parallel RBD is shown in Figure 9. This type of system is analyzed by breaking it down into its basic parallel and series modules and then determining the reliability function for each module separately. The process can be continued until a reliability function for the entire system is determined. The reliability function of Figure 9 would be evaluated as follows:

$$R_1(t) = [\,1 - [(1 - R_{A1}(t))\,(1 - R_{B1}(t))\,(1 - R_{C1}(t))]] * R_{D1}(t) \quad (18)$$

$$R_2(t) = [\,1 - [(1 - R_{A2}(t))\,(1 - R_{B2}(t))]] * R_{D2}(t) \quad (19)$$

$$R_S(t) = [\,1 - [(1 - R_1(t))\,(1 - R_2(t))]] \quad (20)$$

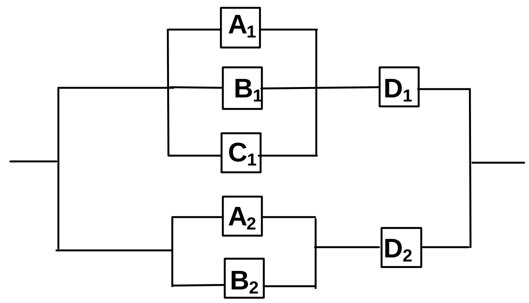

Figure 9. Series-Parallel System

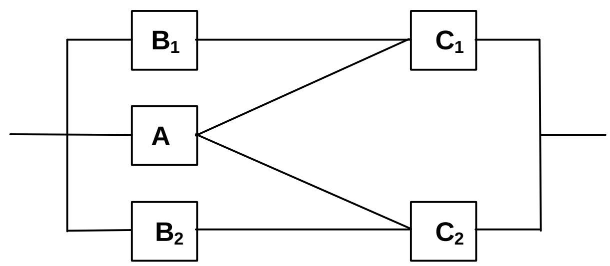

Figure 10. Non-series-parallel system

A non-series-parallel system is shown in Figure 10. One method of analyzing non-series-parallel systems uses the following general theorem:

$$R_S(t) = R_S(\text{if X is working})\, R_X(t) + R_S(\text{if X fails})\,(1 - R_X(t)) \quad (21)$$

The method lies in selecting a critical component (X) and finding the conditional reliability of the system with and without the component working. The theorem on total probability is then used to obtain the system's reliability (see Appendix A).

11. Recommendations

It is recommended that the procedures contained herein be used as guidance toward assessing the reliability of mechanical and electrical equipment for navigational locks and dams. It shall be used to quantify reliability and risk for decision analysis so that upgrade or rehabilitation alternatives can be evaluated.

12. Additional Information

Much of the work covered by this ETL is still under development. The latest information pertaining to the work described herein can be obtained from CECW-EE. Reliability-related Internet web sites are listed in Appendix E.

FOR THE DIRECTOR OF CIVIL WORKS:

5 Appendices
APP A - Non-Series-Parallel System Analysis
APP B - Example of Lock and Dam Mission Reliability
APP C - Mechanical Equipment Example
APP D - Electrical Equipment Example
APP E – Reliability-Related Internet Web Sites

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